CIRS AND CIRS-*LITE* AS DESIGNED FOR THE OUTER PLANETS: TSSM, EJSM, JUICE J. Brasunas[1], M. Abbas[2], V. Bly[1], M. Edgerton[1], J. Hagopian[1], W. Mamakos[3], A. Morell[1], B. Pasquale[1], W. Smith[1]; [1]NASA Goddard, Greenbelt, MD; [2]NASA Marshall, Huntsville, AL; [3]Design Interface, Finksburg, MD.

Introduction: Passive spectroscopic remote sensing of planetary atmospheres and surfaces in the thermal infrared is a powerful tool for obtaining information about surface and atmospheric temperatures, composition, and dynamics (via the thermal wind equation). Due to its broad spectral coverage, the Fourier transform spectrometer (FTS) is particularly suited to the exploration and discovery of molecular species. NASA Goddard's Cassini CIRS FTS [1] (Fig. 1) has given us important new insights into stratospheric composition and jets on Jupiter and Saturn, the cryo-volcano and thermal stripes on Enceladus, and the polar vortex on Titan. We have designed a lightweight successor to CIRS – called CIRS-*lite* - with improved spectral resolution (Table 1) to separate blended spectral lines (such as occur with isotopes). CIRS-*lite* includes four key components:

- high Tc superconductor bolometer/carbon nano-tube (CNT) absorber (~ 87K, YBCO)
- synthetic diamond beam splitter (~ 140K)
- moving mirror mechanism with crossed-roller bearings (~ 110K)
- single crystal silicon for the input telescope primary

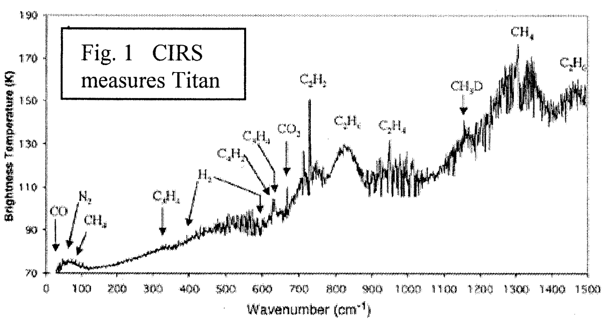


Fig. 1 CIRS measures Titan

Parameter	CIRS	CIRS-*lite*	IRIS Mars	TES	PFS
band-pass (μm)	7 to 1000	7 to 333	5 to 50	6 to 50	0.9 to 45
resolution (cm^{-1}) apodized	0.5	0.125	2.4	5	1.5
telescope diameter (cm)	50	15	4	15	5 /4
detectors	HgCdTe thermopile	HgCdTe high Tc	thermistor bolometer	DTGS pyroelec.	PbSe, PbS $LiTaO_3$
detector temperature (K) **optics temperature (K)**	75 and 170 170	75 and 89 ~150	250 250	Uncooled uncooled	210 and 290 290
point-able mirror	no	TBD 1 kg	no	yes	yes
footprint (km @ 250 km)	1 & 0.05	1 & 0.4	16	2	7 & 14
mass (kg)	43	15 to 20	14	14	31

Table 1: Comparison of planetary FTS's

CIRS-*lite* as a remote sounder operates in both limb and nadir modes. CIRS-*lite* has better spectral resolution and higher sensitivity (due to larger telescope and more sensitive, cryogenic detectors) compared with non-Goddard FTS's such as TES and ESA's Planetary Fourier Spectrometer (Table 1). CIRS/CIRS-*lite* uniquely monitors both the far and mid infrared, a rich source of molecular lines in the outer solar system. The FTS approach is a workhorse compared with more specialized instruments such as heterodyne microwave spectrometers which are more limited in wavelength range and thus the molecular constituents detectable. As such it is well adapted to map temperatures, composition, aerosols, and condensates in Titan's atmosphere and surface temperatures on Enceladus. Additionally, a lighter, more sensitive version of CIRS can be used to advantage in other planetary missions, and for orbital and surface lunar missions.

Details of the four key components for CIRS-*lite* are:

- high Tc superconducting bolometers (Fig. 2) for long wavelengths, about five time more sensitive than the thermopile detectors on Cassini CIRS [2], combined with a CNT absorber.
- chemical vapor deposited diamond beam splitter [3] for 7 to 300 microns wavelength (1000 possible), whereas CIRS needs two beam splitters and two FTS's to cover this spectral range
- FTS moving mirror mechanism (double-passed), with less mass than CIRS yet with four times the spectral resolution.

The increased sensitivity of the long-wavelength detectors enables CIRS-*lite* to employ a smaller telescope and smaller FTS optics while maintaining signal-to-noise (S/N), leading to mass reduction. Further mass reduction comes from replacing two FTS's with one, due to the diamond beamsplitter (Fig. 3). Replacing CIRS' flexure-supported moving-mirror mechanism with double-passed, crossed-roller bearings enables us to achieve a four-fold increase in spectral resolution with no increase in mass or volume (Fig. 4). With this double passing from the FTS optics architecture, we achieve 0.06 cm^{-1} resolution (Rayleigh, unapodized). We have demonstrated the operation of this mechanism under laboratory conditions and near 110K.

- A fourth component helpful for cryogenic operation is the use of silicon optics [4] (Fig. 5). Silicon can be fabricated in an exceptionally pure and spatially uniform state, lessening figure distortion during a temperature change.

The majority of the CIRS-*lite* optics are aluminum alloy (mirrors, mounts, and bench) to maintain alignment at cryogenic temperature (~ 150K). These mirrors are diamond-turned in-house at Goddard, as shown in Fig. 6. Table 2 summarizes CIRS-*lite* as envisaged for planetary missions. The range of wavelength coverage, telescope diameter, etc. will depend on the mission chosen.

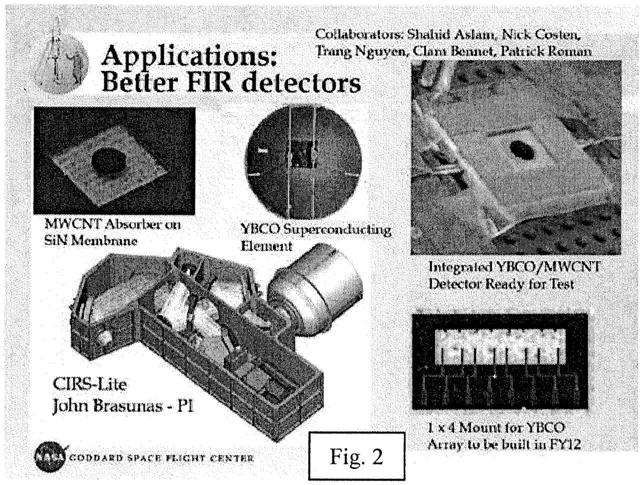
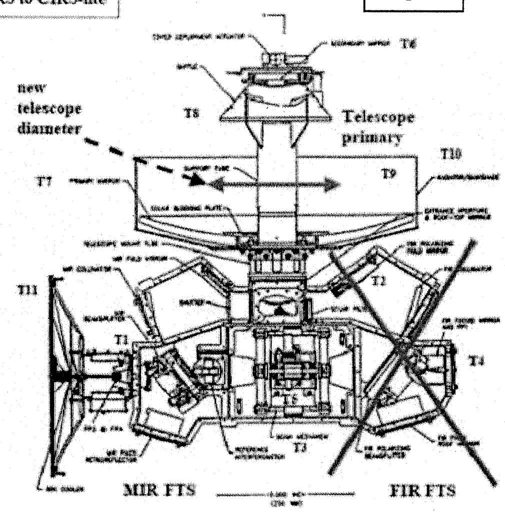


Fig. 2

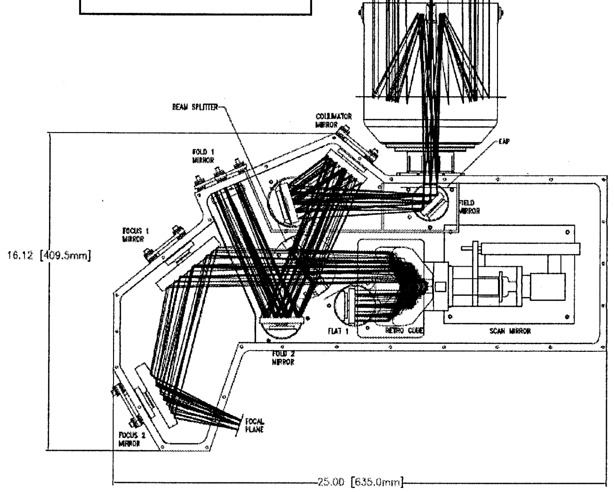
Changes from CIRS to CIRS-lite

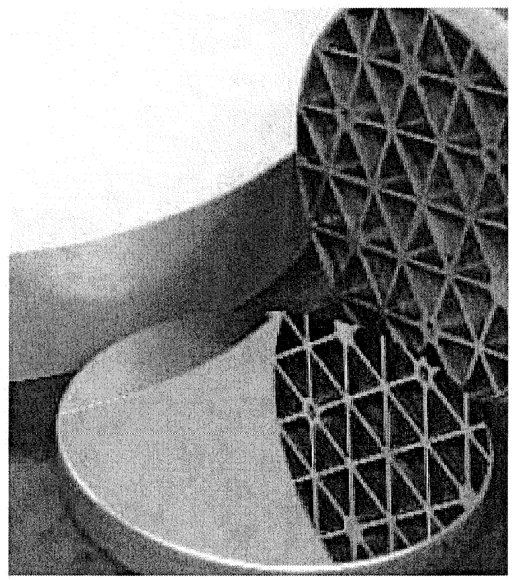
Fig. 3



Cassini CIRS

Fig.4 CIRS-*lite* ray-trace





This image shows the optical surface of a single-crystal silicon mirror reflecting the light weighted, honeycombed backside.

Fig. 5: Fabricating the silicon telescope

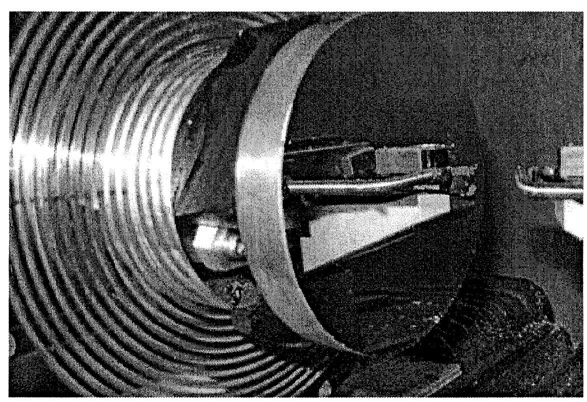


Fig. 6: Diamond turning one of the aluminum mirrors

CIRS-*lite* nominal design (planetary)

- spectral resolution 0.125 cm^{-1} apodized (FTS is double-passed; physical travel is 1 inch)
- spectral coverage is 7 to 333 μm, one FTS with 60 mm diamond beam splitter, no compensator
- detector arrays

TYPE	WAVELENGTH (μm)	PIXEL (mrad/μm)	EXTENT
high Tc	16+ to 333	4.3 x 4.3 / 300 x 300	1 x 4
PC HgCdTe	9+ to 16+	1.5 x 1.5 / 200x200	1 x 30
PV HgCdTe	7 to 9+	same as PC	same as PC

- telescope primary diameter is 15 cm
- there may be a point-able mirror in front of the telescope; similar to the TES design
- optics temperature is 140K (same as Voyager MIRIS)
- all detectors near 70 to 90K, with passive cooler
- collimated FTS beam ~ 3.5 cm -- need ~ 5 cm clear aperture for beam splitter at 45 degrees.

Table 2.

Looking beyond the outer solar system:

Mars and the role of an orbiting FTS From the Concepts and Approaches for Mars Exploration meeting, June 12-14, 2012, Houston, TX
(near term: 2018-2024, and midterm: 2024-2030)

Challenge Area 1: Instrumentation and Investigation Approaches —
Near-term examples include, but are not limited to:
Item 3: **Orbital measurements of surface characteristics such as composition and morphology**
Mid- to longer-term examples include, but are not limited to:
Item 6: **Concepts for measurements of lower atmosphere winds and densities, either globally or at specific sites to support future landing systems.**

And From MEPAG 2010
Goal II: Understanding the processes and history of climate on Mars (Climate)
Objective A: Characterize Mars' atmosphere, present climate, and climate processes under current orbital configuration
CIRS-*lite* is well-placed to characterize global methane distribution and to support orbital measurements of atmosphere in general.

Venus PFS (Formisano) 0.9 to 45 um, 2 cm^{-1}
PFS is designed to measure the chemical composition and temperature of the atmosphere of Venus. It is also able to measure surface temperature, and so search for signs of volcanic activity.

The PFS scanner - the mirror needed by the instrument for pointing - is currently blocked in a closed position, preventing the instrument spectrometer from 'seeing' its targets.

Thus there continues to be a need for a PFS-like instrument at Venus, perhaps CIRS-*lite*?

Future Venus mission possibility – Venera D, whose goal is investigation of the surface, atmosphere and plasma environment of Venus to understand the formation and evolution of the planet and its atmosphere.

Venera D contemplates a PFS-type instrument on the orbiter, as shown below.

Experiments on the orbiter
Solar and star occultation exp UV (0.1-0.3 μm) and IR (2-4μm)
MM-sounder λ =3-10 мм
Spectrometer-Interferometer PFS-VD λ= 1-40 μm, (ν=10000-250 cм-1) Δν= 1 cm -1
UV-mapping spectrometer λ = 0.2-0.5μm, Δλ =0.0004 μm FOV - 5.7°, IFOV - 2 mrad
IR-mapping spectrometer λ = 0.3-5.2 μm, Δλ= 2.4 nm
Multispectral monitoring camera
Radio science 1.L and X range/ 2.UHF -two orbiters

Venera D strawman

CIRS-lite for Earth's moon (surface ice deposits)
Previous lunar missions (Clementine radar and Lunar Prospector neutron spectrometer) have respectively seen indications of water ice or hydrogen deposits in permanently shadowed areas near the south pole on the lunar far side. The neutron spectrometer hydrogen signal may indicate water, or it may indicate hydrogen deposited by the solar wind (predominantly hydrogen), as has the LRO LEND instrument. LRO/LCROSS apparently identified a plume of water released by an impactor, however it is the hydroxyl group that has been measured, and this may be indicative of hydrates rather than water ice. The identification of possible water ice deposits at the lunar south pole is clearly a pacing issue for the lunar exploration program. Spectroscopy may be able to identify the nature of the heterogeneous ice / regolith mixtures that could be present on the moon, with enough quantitative information to specify the concentration (perhaps ~1% by mass) of the ice in the regolith and thus the economic viability of extracting it. Given the presence of impurities, such an understanding may require high spectral resolution; we will need to distinguish between water ice and hydrated non-ice constituents.

The presence of ice would be an important resource for ongoing lunar habitation, supplying water, oxygen and hydrogen. In addition to the usefulness of ice as a resource, study of the ice/regolith mixture will make important science contributions. Unknown are the polar regolith grain size distribution and agglutinate physical properties. We do not know whether the polar regolith is finer grained compared with non-polar regolith. In addition to learning about the regolith, we may learn something about the nature and time history of the source of the polar hydrogen. The source is as yet unknown, and could be some combination of solar wind hydrogen, H_2O and perhaps CH_4 and CO released from non-polar regolith, hydrous meteorites, and comets. Berezhnoy et al. [5] have predicted the delivery of CO_2, H_2O, SO_2 and S to the moon by O-rich short-period comets. They estimate elemental sulfur delivery near the poles at 10^6 g yr^{-1}. Their cold trap capture probabilities for SO_2 and CO_2, respectively, are 2.5% and 25% of the H_2O rate.

Surface-based in-situ (near remote sensing) of permanently shadowed surface ices could be performed in the uv/visible/NIR or in the FIR.
(a) Use a NIR source (thermal, LED, and/or laser) to illuminate the nearby surface and measure the reflection spectrum. The water itself may be present as a minority ice component mixed in with the regolith, or as hydrated non-ice constituents.
Mixtures of ices could be characterized using their IR spectra (Table 3). N_2, CH_4 and NH_3 are examples of other ices which are typically mixed with H_2O-ice; the Apollo program tentatively identified CO, CO_2 and CH_4 in the lunar atmosphere. The identification of other ices in lunar soil would be an important precursor to mining lunar deposits.

Potential Molecular Bands for Analysis

Molecule	cm^{-1}	µm	Spacing, cm^{-1}	Band
CH_4	1304	7.7	10.5	υ_4
CO_2	1063 2349	9.4 4.3	0.75 0.78	hot band, υ_3-2υ_2; also υ_3–υ_1 (961) υ_3 (strong fundamental)
CO	2143.2	4.66	1.92	υ_1–υ_0
NH_3	3335.9	3	~20	υ_1
C_2H_2	729	13.7	~2	υ_5
C_2H_6	825	12.1	2.6	υ_9
N_2O	1285	7.8	0.84	υ_1
HCN	712	14.04	3.1	υ_2

Table 3

To get depth information of the icy near-surface deposits, we could use a laser source or ultrasonic generator to heat/agitate the surface and drive off a volatile plume to be measured in the gas phase.

(b) Measure surface icy deposits in emission in the FIR (40 to 100 microns). The low surface temperatures (< 100K) of permanently shadowed regions means emission measurements must be done in the FIR. Astrophysics measurements of interstellar dust grains have identified lattice features of water ice: [6] shows these astrophysical data superimposed upon the spectrum of crystalline laboratory ice. The far infrared bands of water ice were observed in a circumstellar shell, where water is the dominant grain constituent. The FIR bands are produced by translational modes in the lattice and is thus a sensitive function of the deposition mode. Crystalline ice has two peaks in absorptivity; in amorphous ice, the longer wavelength peak is suppressed.

It is not assured that the FIR features will be present even if water ice is present. A temperature gradient is also required when looking at optically thick targets, and this is expected to be a contributor to the non-detection of this water ice feature in Voyager IRIS data. Nor was it seen in icy comets [7]. In the case of the lunar regolith, it may help that the thermal conductivity of slowly deposited amorphous water ice is 10^4 times smaller than crystalline ice [8], coupled with a lunar heat flow.

Recent NASA GSFC development of MgB_2 superconductor bolometers (Tc near 37K) are especially attractive for this application[9], as these bolometers appear to be significantly faster than YBCO detectors operating near 87K.

Earth

Earth's spectrum longward of 15 microns is largely unexplored, and various groups propose monitoring it for climate studies, as could CIRS-*lite*.

REFIR (Italy)/FORUM targets 0.5 cm^{-1} resolution, covering 100-1100 cm^{-1} for rotational water vapor. These designs include a bore-sighted imager for cloud identification (thermal IR), and a broad-band radiometer. Technical challenges include the beam splitter efficiency, and the relatively insensitive pyroelectric detectors.

FIRST (NASA Langley) also targets water vapor , extending Earth monitoring from the current ~ 15.4 µm to 100 µm. This concept continues to FIREX and CLARREO.

Both the Italian and US efforts begin with balloon systems, and attempt to extend these to space missions. CIRS-*lite* could do something similar.

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